REFLECTIONS ON SATELLITES FOR EARTH RESOURCE SURVEYS: PERSONAL CONTRIBUTIONS TO A SUMMER STUDY

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PREFACE

The National Aeronautics and Space Administration sponsored a study in the summer of 1967, conducted by the National Academy of Sciences, on Earth-Oriented Space Applications. The study is continuing, and there will probably be another summer devoted to this same subject. The author had the pleasure of participating in Section 1 of this study while on vacation, and the material that follows is what he produced for it.

In preparation for and as an input to the summer study, NASA produced A Survey of Space Applications (NASA SP-142), dated April 1967. Because it is an elegant and complete statement, Mr. James Webb's foreword is quoted in its entirety below.

FOREWORD

> The second half of the 20th century is characterized by an explosive increase in the powerful instruments available to mankind in the shaping of its destiny, for either good or for evil. New technologies have grown so rapidly as to offer a wide array of capabilities from which the leaders of the society are able to choose their tools in the pursuit of their goals. Significant among these are the technologies that have been expanded or created in response to the drives for the exploration of space, an exploration not yet 10 years old.

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But, if our age is characterized by the burgeoning of new forms of power, so has the history of our Nation always reflected the search for wisdom in the use of that power. One of the major avenues of intellectual and program effort that have guided the National Aeronautics and Space Administration has been the concept, at first unproved but now clearly valid, that space systems can provide unique, direct benefits to man, benefits not before possible or economically feasible. We do not yet know the full range and scope of the possibilities that manned and unmanned spacecraft open for the service of man. Those few particular applications upon which the United States has concentrated in the past have borne out that promise: Communications, navigation, geodetic, and meteorological space systems are operational today and their existence, once exotic, has already become woven into the permanent fabric of our society.

It is clear that many potential applications exist; it is not clear today which of these should be pursued, nor on what time scale, nor at what cost. Beginning in the summer of 1967, the National Academy of Sciences is conducting a study that will bring to bear upon these questions eminent independent scientific and technical talent. NASA is pleased to encourage and participate in such a searching inquiry, since only through such a free exchange of ideas in a free society can true progress be made or a sound basis for the major decisions of the future laid down. This survey of space applications for the benefit of man represents the current NASA thinking, has incorporated as many as possible of the views of our colleagues working in those areas which we feel space can serve, and is published as a source and document baseline for continuing discussion and inquiry in this important area.

James E. Webb,
Administrator,
National Aeronautics and Space Administration.

The summer study was divided into two consecutive three-week sessions. Section 1 was devoted to Earth Resources; Section 2 was on Communications. At the end of the six weeks, there was scheduled a two-week meeting of the Central Review Committee to blend, integrate, review the diverse papers, and prepare the final report.

Section 1 was divided into panels dealing with Oceanography, Meteorology, Cartography and Geodesy, Earth Resources (Agriculture, Forestry, Geophysics, Geology), and Sensor and Data Handling.

About 50 people participated in Section 1. There were many briefings by outside sources, much panel interaction and discussion. As stated in the author's cover memo (which follows this Preface), "three weeks is far too short to simultaneously listen, learn, read, talk, and write." The reason three weeks is too short is precisely that these various activities cannot be conducted simultaneously; each is competing for the same slice of time.

What the author prepared is only one input of many and is his alone. Some copies of this set of six short papers have received inadvertent but nevertheless very wide distribution and comment in both government and industry. This is a testament not only to wide and proper interest in the subject, but to the efficacy of modern reproduction systems. Requests have come in for additional copies. Hence the decision to make them available in this form.

There appeared to be little point in rewriting these papers -- not because they are so complete, comprehensive, and well-written. Far from it. These papers were, obviously, hastily written and preliminary only. Except for copy editing, what follows is what was written, not what should or could have been written. The reader is urged to keep this in mind when he discovers or uncovers lacunae or misemphases.

The problem of discovering new resources, of managing existing resources, of helping developing countries help themselves; the dimensions of the world food problem and the partly teasing, partly plausible, partly demonstrable hopes dangled by technology -- will continue to ensure high and continuing interest in this general subject. For exactly the reason that the problems are real, large, serious, and consequential -- it is necessary to devote more than a good heart and generalized pieties to solution of the problems. Every topic treated by the author demands fuller exposition -- and many topics have been left out.

A word of thanks and appreciation must be extended to the writer's fellow participants in the summer study. I learned much that was completely novel to me. Thanks must be extended to the National Academy of Sciences for agreeing to independent publication of my contribution in this form. This publication and this agreement does not imply that anyone, any agency, the National Academy of Sciences, or The RAND Corporation agrees with my findings or arguments, or that any of these ideas will be found in the final report of the summer study. As of October 1967, the writer has not seen any of the reports of Sections 1 or 2, or the final summer study report.

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COVERING MEMO July 12, 1967

TO: Director, Summer Study; Chairman, Session 1; Central Review Committee, Panel Chairmen, Panelists

FROM: Amrom H. Katz

SUBJECT: Six Attached Papers and Related Thoughts

As of this date, I have finished six short papers, which in my judgment bear directly and heavily on some major issues and themes flushed out by the current summer study exercise.

The titles are as follows.

I. The Case for Aircraft in Earth Resource Surveys

II. Discussion of a Proposed Aircraft System for Earth Resource Surveys, or How to Meet all Requirements with Men in Aircraft

III. Discussion of a Hypothetical Photo Satellite System for Land Use Survey

IV. Facing the Analysis Problem

V. How to Start

VI. The Limiting Case

As I listened, read, and talked, it seemed to me that two huge areas were unlikely to receive adequate treatment -- the role of aircraft and the need for a BIG analysis center. Further, it seemed fairly clear that meteorology and oceanography (except for coastal areas) are not "natural" applications for photographic techniques (again, in the case of meteorology, where pictures are relevant, that subject is in good shape).

Hence the concentration on land use and earth resources. The land is where the people are, and where most of the money in the business of this summer study is likely to be made.

The mapping/cartographic group here is both capable and autonomous; hence nothing of what is written is directly about their work.

On the first day here, I distributed numerous copies of my 1959 paper Observation Satellites: Problems and Prospects.* This paper contains information about resolution and its meaning, cameras, information rates, and, especially, a discussion and comparison of read-out versus film recovery systems. It would have been pointless to retype that fairly elementary material, and besides, more recent and more technical material is available through G. C. Brock.

I hope these brief words will help explain my choice of topics, emphasis and treatment. Much more could have been written about the topics included; other, perhaps even more important, topics were omitted. However, there are personal bandwidth limits. Three weeks is far too short to simultaneously listen, learn, read, talk, and write.

Amrom H. Katz

*Amrom H. Katz, Observation Satellites: Problems and Prospects, The RAND Corporation, P-1707, May 1959; also published in Astronautics, April, June, July, August, September, October, 1960.

I. THE CASE FOR AIRCRAFT IN EARTH RESOURCE SURVEYS

From the standpoint of science, the earth is, as Wendell Willkie put it, one world. The oceans lap all shores with impartiality, paying little heed to political lines drawn on paper maps. The sun shines on all -- with differences attributable only to sines, cosines, and the calendar. And the atmosphere affects all, driven by the sun, and responding to the earth surfaces below, but supremely indifferent to political boundaries. As long as man has been on earth, he has responded to and been affected by these vast forces, and he has both used and abused the resources of the earth.

Earth resources have been lying around outside for many years. Whether exploited or unexploited, they have not been ignored by consumers, scientists, industry, and governmental bureaucracies. Aircraft, air photos, and the science of using them to map vast areas are not new.

So why the recent and continuing excitement about earth resources survey from space? Is it reasonable or proper to regard this idea as heralding a new subject? Or is it that the advent of a new tool -- earth-orbiting satellites -- makes possible the accomplishment of tasks not previously possible? Let's look at these questions.

The earth is one, but U.S. government agencies have carved it up into separate fiefs. Weather belongs to Commerce, trees and crops to Agriculture, and rocks to Interior. There are other assignments. Now, as government agencies go, the U.S. Geological Survey is ancient. It has been using air photos for many years.

Though satellites are comparatively new, the possibilities of doing from satellites what is now being discussed were published by the writer about ten years ago.* We must look deeper.

Two factors remain. First, but not most important, is the advent of the multisensor business. Aerial photography, with only minor exceptions, has been seeing and portraying what the human eye sees. Because longer focal length lenses and/or wider-angle lenses than the eye can be used, and above all, because photographic film can produce a permanent record for leisurely analysis, photographs have proven very useful. But since the post-World War II years, we are witnessing the introduction of high-resolution radar imagery, infrared imagery, and other sensors that reveal things about the earth, what grows on it, and the artifacts and patterns introduced by man. Both these tools "see" what the eye can't see -- either through clouds or in darkness. Photography -- even aerial photography -- is off to a 100-year head start, so it is neither fair nor sensible to compare the well-developed uses, analytic techniques, and production base of aerial photography with the experiments, lack of systematic interpretation tools, and shortage of "customers" in these newer areas of "vision."

The second factor is more important, and we might as well say it straight. NASA, or more properly a small section of NASA, has seized the bull by the horns. In an enthusiastic, imaginative, wide-ranging synthesis, necessitating the expenditure of considerable energy and

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*P-1707.

drive, NASA has made a subject out of these far-flung and disparate ideas, experiments, and aspirations. Never mind that the task could have and should have been done long ago. They did it, and now is better than later.

On the assumption -- made more solid by NASA officials briefing the participants in the summer study -- that the first "A" in National Aeronautics and Space Administration is not there solely to facilitate pronunciation of the acronym, we should consider the use of aircraft for doing the various jobs subsumed under the title of "earth resources survey."

There is no requirement at this time for an extended comparison and discussion of the political palatability of aircraft and satellites or of the acceptability (in bi- or multilateral cooperative arrangements) of each system.

It should be pointed out that the ground tracks of earth orbital machines, especially if they are in high-latitude orbits (i.e., near-polar), pass over every country. And if a bilateral arrangement is made with country A, contiguous to or near to countries B and C -- who might object to being observed -- then there can and will be unpleasant and nontechnical problems. It is very hard, in fact impossible, to orbit a satellite over only country "A". Further, it would seem reasonable that, if we have bilateral agreements with, say, only countries A, B, and C, no one will believe that we are seeing and collecting data only over A, B, and C, no matter how solemn the declaration. The patently poor economics of so operating would only add to the strain on everyone's credulity. We had better keep our political feet on the ground while getting our technical seat into space.

This congeries of problems need not arise with aircraft. As will be shown later, aircraft operation is inexpensive compared with satellite operation. Even more relevant to the discussion immediately above, the aircraft system consists of a group of aircraft, any number of which, down to one, can be assigned to any area. Thus the size of the effort can be tuned to the size of the area proposed for coverage.

There is another important factor which makes aircraft preferable. One of our oft-stated assumptions (or axioms) is that for the United States to engage in a bilateral assistance agreement with country A, that country must do something itself, aside from being the (un)grateful recipient of assistance. They should participate as much as possible. Now, suppose we tell A that we've got a satellite that will fly over A and deliver data about A. The people of A never taste, smell, hear, see, or touch the satellite, before or after launch. The "political participation benefit quotient"* for the satellite is close to zero.

If we cover A by an aircraft system, it can be based in A. (To the writer's knowledge, there is no country in the world where we can't land a 707-type aircraft. If an exception exists, that place had better get about joining the jet set.) Nationals from A can fly in the aircraft; it can be made the object of press releases and other publicity. This point need not be expanded here. For

*This expression is not standard -- yet. It was freshly minted for this paper.

aircraft, the "political participation benefit quotient" is measureable and is far greater than that for satellites.

However, the argument will not be settled, nor even made conclusive, without some cost estimates. We now turn to that topic.

II. DISCUSSION OF A PROPOSED AIRCRAFT SYSTEM FOR EARTH RESOURCE SURVEYS, OR, HOW TO MEET ALL REQUIREMENTS WITH MEN IN AIRCRAFT

In this section we will discuss a system for securing earth resource data over large areas. We are excluding meteorological coverage and systematic coverage of the open oceans, except of those waters near shore. "Near shore" is deliberately vague and adjustable.

We assume that <u>with sufficient R&D</u>, the collection of multichannel imagery in the visible, infrared, and microwave regions can indeed be used as a high-confidence method of identifying and mapping the desirable quantities that the geologists, geographers, foresters, agriculturalists, urban area analysts and others have elsewhere specified. We state as an axiom that <u>before these tasks can be accomplished from satellites they can be accomplished from aircraft</u>.

We have been shown some exciting, stimulating examples of what can be seen from Gemini photos. To this observer this comes as no surprise.* As a minor historical note, of little public but high personal interest, an ancient experience is worth a few words.

By 1952, the writer had already spent a dozen years doing and looking at aerial photography from what were then high altitudes of say 30,000 to 40,000 ft. Having heard that The RAND Corporation was studying satellites designed to operate at 200 to 300 mi altitude, the writer decided to prove that nothing useful could be seen from such altitudes. Managing to obtain two very short focal length

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*See Robert W. Buchheim and the Staff of The RAND Corporation, <u>Space Handbook: Astronautics and Its Applications</u>, The RAND Corporation, 1958; and P-1707.

lenses (with comparatively great back focal distances, i.e., from the rear surface of the lens to the focal plane), the writer adapted and mounted them on a Leica and personally took photographs with the 7.5 mm and 15 mm focal length lenses from a 30,000-ft altitude. Enlargements were a shock, for they showed the streets and bridges of Dayton, Ohio, as well as many other features. For the shorter of the two lenses, the scale number in the vertical is readily calculable to be 1,200,000!

However, despite the exciting photos and the occasionally clever analyses, we have heard no one willing to claim that the state of the art in analysis will now permit useful world-wide surveys at a ground resolution of 100 to 200 ft. These photos would be taken three at a time using different portions of the visible and near-infrared spectrum. The tonal variations in these three bands would represent a sort of three-combination safe, which, when unlocked, would permit identification of the contents. We have heard only that more R&D is necessary on this concept. G. C. Brock is preparing a careful statement about the meaning of the widely-used term ground resolution for the summer study, so there is no need to expand this point. The papers cited earlier contain discussions of this subject which are adequate for most purposes.

Discussion with users seems to suggest that what they'd really like is a multichannel spectral response measurement from about .4 to 15 μ. This could be provided by a University-of-Michigan-type spot scanner.

Other users, particularly the geologists, find unique merit in the high-resolution sidelooking radar proposed by R. Moore in another paper prepared for the summer study. Many land use experts are charmed with the results obtained on Kodak Ektachrome Infrared Aero Film Type 8443, a color film (originally developed to detect camouflage) in which one of the three sensitized layers has been replaced by an infrared sensitive layer. In developing this film the infrared responsive layer shows up red. This combination yields interesting images. On the other hand, standard Aero Ektachrome also yields results of much interest.

The way we propose to handle these requirements (note that interests have become requirements) is to meet them all.

We are proposing, therefore, that the aircraft collection system described below include the following equipment:

1. High-resolution sidelooking radar (characteristics supplied by R. Moore in his summer study paper).

2. 20-channel recording spectrophotometer (.4 to 15 μ) with 3-millirad resolution (details by D. Lowe in his paper) and 120° coverage.

3. Three high-resolution panoramic cameras (detailed description below), filtered to cover the required three spectral bands:

   a. Infrared -- .7 to .92 μ (89B filter)

   b. Panchromatic -- .6 to .68 μ (Pan 25A filter)

   c. Panchromatic -- .52 to .62 μ (Pan 58 filter)

4. Three 6-in. (wide angle) metric cameras, covering 9 by 9 in. One of these cameras will carry conventional panchromatic film; the second will take photos on Kodak Ektachrome Infrared Aero Film; the third will use standard Aero Ektachrome.

The panoramic cameras will use 70-mm film, cover about 120°, and be fitted with 6-in. lenses. 80 lines/mm is a realizable and conservative performance figure on high-resolution aerial film. At about a

40,000-ft altitude, this yields a swath width of about 30 mi. The resolution in the vertical (at the nadir) is given by:

$$\text{GROUND RESOLUTION IN FEET} = \frac{\text{SCALE}}{300 \times \text{Resolution (in lines/mm)}}$$

A 6-in. lens at 40,000 ft yields a scale number S = 80,000.

Hence: $G_{vert} = \frac{80,000}{300 \times 80} = 3.33 \text{ ft } (\approx 1 \text{ m})$

The photography at the edges of the position 15 mi off vertical (30-mi swath) is at a slant range of about 80,000 ft. S_x, the scale in the horizontal in direction of flight, will be about 160,000, and S_y, the scale number perpendicular to the flight line, will be 320,000. Similar calculations for ground resolution at the edge of the field yield:

$$G_x = 6.67 \text{ ft } (\approx 2 \text{ m})$$

$$G_y = 13.33 \text{ ft } (\approx 4 \text{ m})$$

It is useful to define the mean ground resolution $\overline{G}$:

$$\overline{G} = \sqrt{G_x \, G_y}$$

In this case, this yields:

$$\overline{G} = 9.5 \text{ ft (about 3 m)}$$

Thus resolution falls off from about 1 m in the vertical to about 3 m at the very edge of the field, 15 mi off vertical. <u>It should be noted that these performance numbers meet or exceed all specifications and hopes for every job in which resolution is a key factor</u>.

We propose using 70-mm film. We propose calculating our film requirements on the assumption that stereo photography will be taken. Now it is not general practice to take stereo photos in two different spectral regions, but it is possible, and with the three proposed cameras we get three viewing combinations: cameras 1 and 2, cameras 2 and 3, and cameras 1 and 3. Of course, each single camera can produce stereo photos by simply taking two photos of everything, separated by some airbase between photos. This is conventional.

If it turns out that stereo is not desired, or not useful, or not useful enough, this cuts our film load by more than a factor of 2.

To calculate film requirements, observe that the 70-mm film gives a useful field in line of flight of about 2¼ in. This, with the 6-in. lens at a 40,000-ft altitude, means ground coverage in line of flight of 15,000 ft. To take stereo photos with 60 percent overlap, successive photos are taken every .40 of 15,000 ft, or every 6000 ft of aircraft travel. Remember that we proposed covering about 120° across the line of flight. The length of each photo is, therefore, $(2/3)\pi \times 6$ in., or about 12.5 in.

If we fly a flight line of say 3000 mi and advance the film every 6000 ft, we will be taking about 2600 photos per sortie, and the film requirements will be much less than 3000 ft per camera. Let's use 3000-ft rolls. Such a roll of film, on thin base, will weigh about 16.5 lb, plus the weight of the spool, so the total is less than 20 lb. (We're going to carry this in a great big airplane, so this figure is supplied not to comply with a payload budget, but to satisfy the curiosity of the reader.)

So much for the panoramic cameras. The photos produced by panoramic cameras can be used for map revision, and they can be rectified to look like a vertical photograph. For most purposes, however, they need not be rectified.

The three metric cameras are conventional 9 by 9 in. format, with 6-in. focal length lenses. The resolution that could be expected would be about a third to a half as good (meaning twice the numerical values) of that obtained with the panoramic cameras.

These cameras, covering an area 60,000 ft on a side from a 40,000-ft altitude, would be used for plotting ground tracks, and the two color-carrying cameras would be useful in checking and comparing integrated color representations against the several separate sensors and films used in the other equipment. Each of these cameras would carry about 750 ft of 9½-in. film.

Now what will all this cost and how much can it do? We propose considering, as an illustrative example, covering all of North and South America and Greenland, an area of about 17×10^6 mi^2, or 12.7×10^6 n mi^2.

The following analysis is tunable and contains sufficient data on assumptions and operations to allow extrapolation or interpolation for larger or smaller jobs and for more or less frequent coverage.

We will buy a fleet of ten 707-type aircraft (or C-135's) equipped as described above, and amortize them over ten years. We will fly them <u>only 35 hours a month</u>. (Note that commercial airlines would go broke instantly if they used their aircraft as little as four times this rate, i.e., if they used their aircraft only 120 hours a month!) Operation and maintenance costs for such an aircraft include POL (fuel), spares, and maintenance. We will be more than generous in estimating crew size and salaries. The aircraft would have to be moved to new operating bases (staged) several times a year. These costs are estimated. A huge amount of data will be collected on each sortie, and the flight lines must be plotted and the film developed before it is turned over to the analysis group. A generous estimate of this cost is made. We will be conservative and allow an active flight line of 3000 mi per sortie, and five sorties per month.

The costs can now be tabulated for a purchase of ten aircraft.

Item	Annual Cost
10 707-type aircraft @ $\$5 \times 10^6$ each (amortize in 10 years)	$\$5.0 \times 10^6$
10 equipment packages as described above @ 2×10^6/package	2.0×10^6
Operation and maintenance @ \$500/hour 10 aircraft x \$500/hour x 35 hours/month x 12 months/year	2.1×10^6
Crew salaries, 10 crews @ 7 men/crew @ \$20,000/year	1.4×10^6
Staging costs for 10 aircraft, several stages/year	1.0×10^6
Processing and plotting costs @ \$10,000/sortie 50 sorties/month x 12 months = 600 sorties allow 1/3 failure rate, yielding 400 good sorties, and process and plot at $\$10^4$/sortie	4×10^6
TOTAL ANNUAL COST	$\$15.5 \times 10^6$

A coverage per sortie of 3000 mi x 30 mi = 9×10^4 mi^2. 400 good sorties a year yield a coverage of 36×10^6 mi^2, <u>or two looks at everything in North and South America</u>.

$$\text{Cost/mi}^2 = \frac{\$15.5 \times 10^6}{36 \times 10^6 \text{ mi}^2} = \$.43/\text{mi}^2$$

If the reader, who has been hearing commercial mapping costs of $\$2\text{-}4/mi^2$, wonders how this financial breakthrough has been achieved, let him look at the details. Commercial photography is produced slowly, over small areas, at low altitudes. We have designed a production system.

No direct comparison with a satellite system can be made, because no one dares to design a satellite system that will deliver this volume or quality of data.

However, in a subsequent section we will estimate the cost of a much more modest photographic satellite system, getting resolutions that are inferior by a factor of 5 to the system described herein, and it will be shown that to cover only 80 percent of North and South America will cost at least an order of magnitude more than with aircraft.

One final note. It was said earlier that this proposal is tunable -- i.e., that to go over some small country one can peel off one or two of the aircraft. To peel off in a quick response to some disaster, whether man-made or natural, one can assign an aircraft to cover the area at high frequency. This proposal is also tunable and scalable in another sense. If more or less looks per year are desired, the number of aircraft can go up or down proportionately.

III. A DISCUSSION OF A HYPOTHETICAL PHOTO SATELLITE SYSTEM FOR LAND USE SURVEY

The following analysis is not rigorous, but heuristic. Whenever possible, assumptions are displayed, permitting and encouraging argument, correction, and verification. In particular, one can scale up or down and see what happens.

We will take without argument the requirements stated by the earth resources people on panel B. They will settle for 100-ft resolution, and they want square, single photos showing about 100 mi on a side. They want these photos taken in the by-now-well-known (but unproven) spectral bands listed below:

Band 1	.7 to .92 μ, using 89B filter
Band 2	.6 to .68 μ, using 25A filter
Band 3	.52 to .62 μ, using 58 filter

These modest requirements can be met with various combinations of resolution obtained in the cameras, focal lengths, film sizes, and altitudes. The basic equation connecting ground resolution G in feet, altitude H and focal length F (where H and F are in the same units) and resolution obtained on the film in lines/mm is

$$G = \frac{H}{300RF}$$

(This is of course, the same equation as $G = \frac{S}{300R}$, where S is the scale number.) If one assumes that R = 50 L/mm, G = 100 ft, and H = 125 n mi, then F = 6 in., a not unreasonable result.

Using 5-in. film for the image, the coverage of a 6-in. focal length camera at the assumed altitude will be 5/6 of the altitude, or just over 100 n mi square.

So far, everything is easy. Now let's launch our three-camera satellite into a near-polar orbit. Assume a 12 to 16 day life. We intend to recover the photographic film. Why not stay up longer and collect more and more data? The best practice is to avoid the temptation; for just as a child may not be able to get his hand out of the cookie jar if he grabs too many cookies, reliability factors in delayed recovery may prevent getting anything at all back. One day's operation is too short, and two months' operation veers toward the cookie-jar syndrome. Two weeks is reasonable. Note that this is based on one spit-back per satellite. If we could invent an orbital six-shooter (a satellite that fires back film loads at intervals), we could contemplate longer operation. But this would cost somewhere in the system.

If the orbital period were an integral submultiple of the day (for example, if the orbit were exactly 90 minutes, since 90 minutes is 1/16 of the day), the satellite ground tracks would repeat themselves, and we'd keep covering the same 100-mi swath over and over. This sad eventuality can be avoided by choosing the orbital height. For circular orbits of height H, a convenient relationship is:

$$\text{ORBITAL PERIOD IN HOURS} = 1.41 \left[\frac{R + H}{R}\right]^{3/2}$$

where R is the earth radius.

The assumed altitude of 125 n mi avoids this problem. It is left as an exercise for the student to show that it is on a nine-day screw-thread, repeating its track every nine days. In two weeks, then, about 1.5 "looks" at whatever it sees are available.

But the satellite ground swath is 100 mi wide. If it is tuned for the equator, so that it just nicely lays one path next to another without excessive overlap, it will "overkill" in the northern and southern latitudes, for the orbit tracks converge. Conversely, if the path intervals are right for the higher latitudes, there will be gaps at the equator. The efficiency of this operation is low.

However, clouds and other obscuration are the real curse of this business.

Again take, as in the aircraft system proposed earlier, the job of covering North and South America. The cloud statistics over the United States' latitudes are not bad, especially when compared with equatorial areas.

Cloud cover statistics are tricky, and their interpretation even trickier. Does .8 cloud cover mean that there is 80 percent cloud cover all the time, or does it mean that 80 percent of the time there is 100 percent cloud cover, or what?

Neglecting these semantic and data problems, it would appear that the chance, over the year, of getting relatively cloud-free photography over this huge area is only about 30 percent.

Calculations in some DoD studies of similar and also hypothetical satellites have shown that it would take twelve satellites in a year to cover only 80 percent of the total area -- once. How come? Well, the first satellite has the whole of both continents to pick from. The second, third, etc., are busily working on ever-shrinking areas. The series doesn't converge fast enough -- and after twelve satellites, we've still got 20 percent left to go. It would cost another twelve birds to get 80 percent of that 20 percent!

The estimated cost per launch -- booster, payload, tracking, command, and recovery functions -- can be between eight and ten million dollars. Taking the middle value of nine million, we get an annual cost of about 100 million dollars -- for 80 percent of 17 million square miles, or

$$\frac{\$10^8}{17 \times 8 \times 10^6 \text{ mi}^2} = \$7.60/\text{mi}^2$$

-- for an incomplete job!!!

Remember the cost of doing this whole area twice with aircraft was about $\$.43/\text{mi}^2$. This is a ratio of 18:1 (satellite costs/aircraft costs).

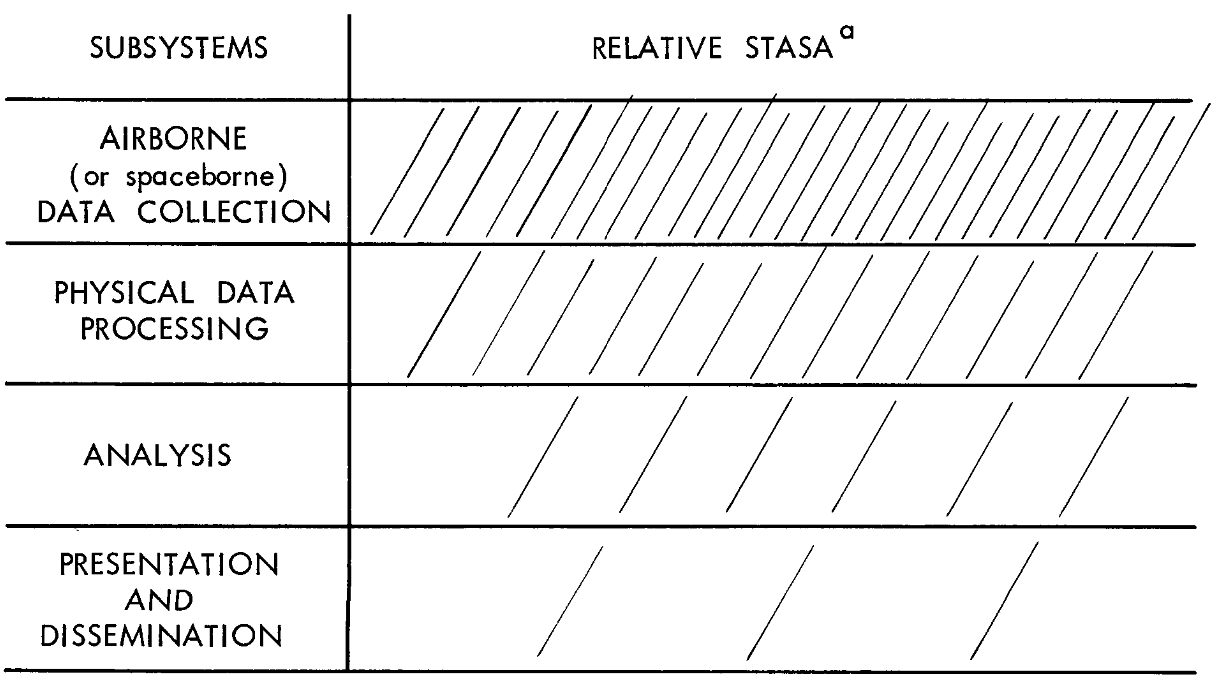
Remember, too, that with an aircraft system we would obtain 20-channel infrared coverage, radar coverage, and aerial photos with 3- to 9-ft ground resolution, which is from ten to thirty times better than that obtained from orbit.

IV. FACING THE ANALYSIS PROBLEM

It is one thing for a briefer to project a few Gemini photos and then expound at length on what can be seen. It is quite another to contemplate what will happen when the flood-gates are opened and new data pour from the sky.

The analysis and data-handling problem is usually ignored, and when not ignored is always downplayed and underestimated. Let's see why.

Most answer-acquiring systems can be subdivided into four subsystems -- airborne data collection, physical data processing, analysis, and presentation and dissemination. Now, were an airbrush used to spray ink on each of these rows in proportion to the attention, interest, dollars, priority given it -- to sum it up, its scientific/technical/administrative sex appeal -- the distribution would look something like the sketch below.



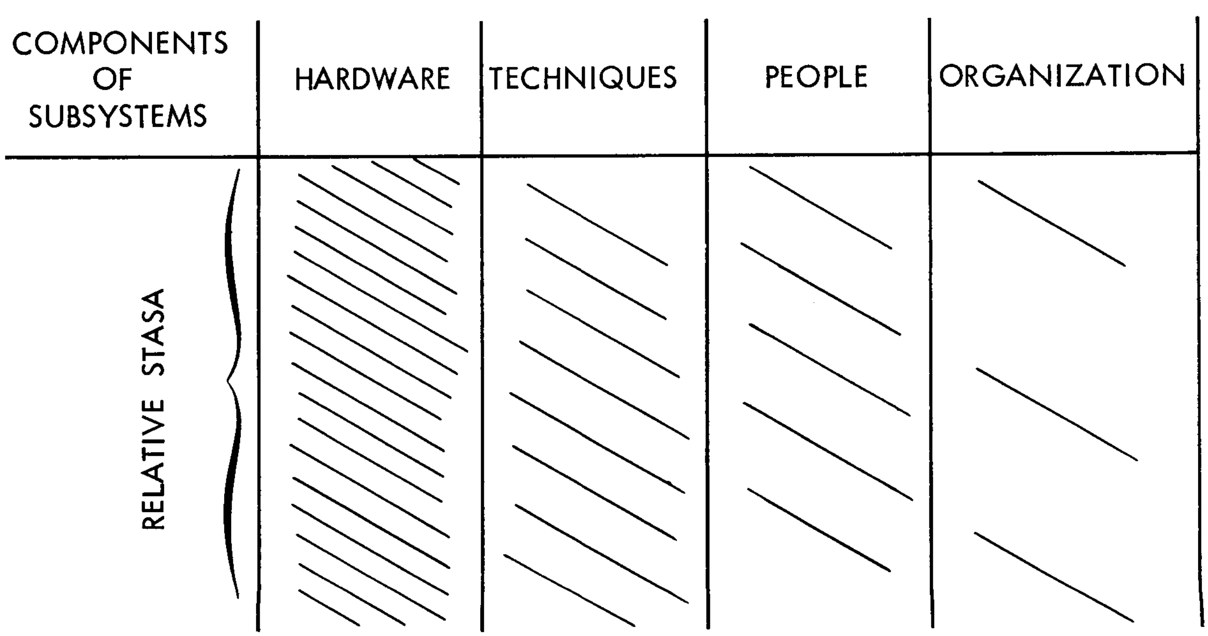
[a] SCIENTIFIC/TECHNICAL/ADMINISTRATIVE SEX APPEAL

Most of the effort, as measured by priority, attention, interest, and dollars, goes into the glamor stock -- the collection subsystem. And the successive subsystems get less and less effort.

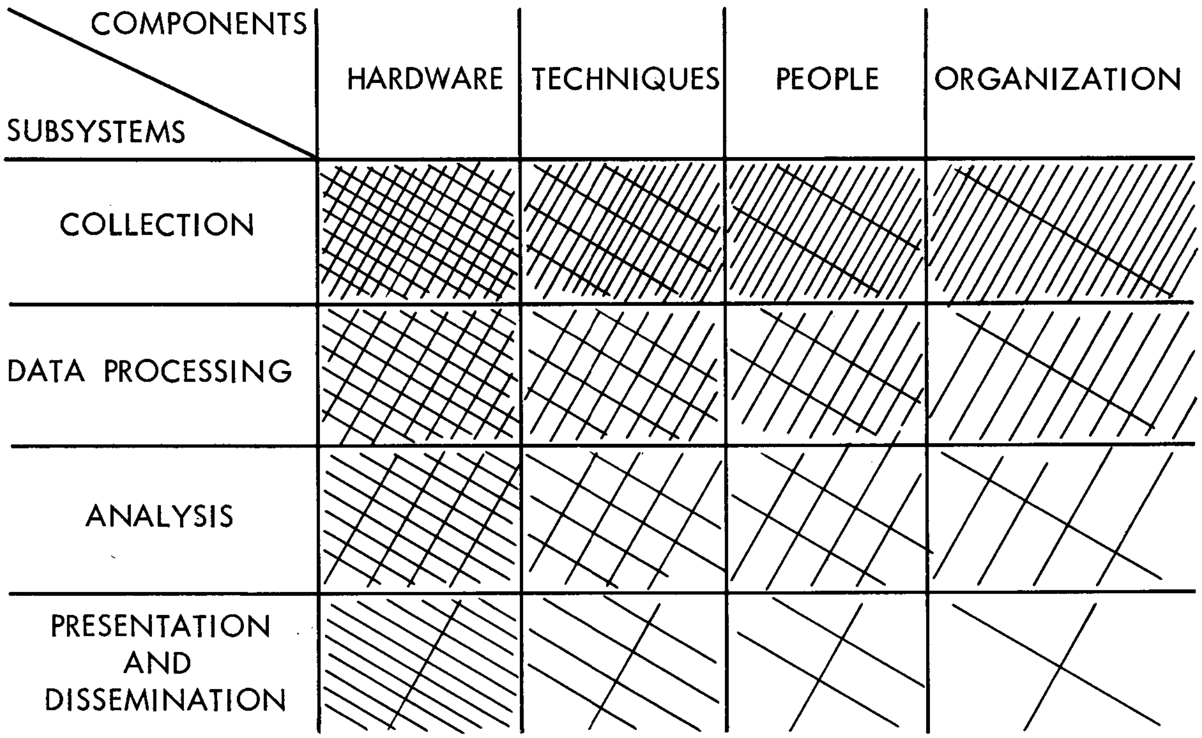
To say in short form what deserves lengthy discussion, photo-interpreters may aspire to the rank of major, but pilots can become generals. The action (and the money) is where the data are collected.

Were this same answer-acquiring system subdivided in the other direction, we would find that most such systems can be broken into four components -- hardware, techniques, people and organization. By "people" we mean the training, hiring and firing of the personnel in the system. By "organization" we mean the relationship between this system and other organizations, such as consumers, R&D labs, etc.

Taking up the ink-filled airbrush again, and spraying these four columns in proportion to the effort applied, we find a distribution similar to the first one but at right angles to it.



Superimposing these two charts, we get the following:



Everything piles up in the northwest corner -- in collection hardware! Analysis techniques, to pick one of the softer, but critical, pieces of the pie, get short shrift.

This can be avoided only by paying much more attention to this problem earlier in the game. Further on in this paper we will develop cost estimates for doing global, or near-global, surveys properly. Science, industry, and the taxpayers will not long stand the notion of hundreds of millions of dollars being accelerated up off the launch pad without many beneficial results coming back.

Take our previously used example of North and South America, which is about 1/3 the land area of the world. Consider the numerous questions already raised (and those likely to be raised after data are in hand) about distribution of crops, yields, forest lands, transportation and urban patterns, etc., and the varied forms in which both partial and completed data will be stored, presented and used.

When we realize that multisensor imagery and nonimagery data will be collected, that they will have to be filed, plotted, duplicated, enlarged, reduced, and combined, that mosaics may be made, maps produced, both true and false color prints made, specialized atlases and encyclopedias published (to lift the lid only slightly on our Pandora's Box) -- we can discern the magnitude of the required effort.

Let's estimate the cost of analysis. We assume that coverage of the area will be obtained several times per year, and that there will be some number of smaller areas requiring special study and more frequent or more concentrated coverage.

Our analysis center will have imagery interpreters, specialists in photo, radar, and infrared interpretation. (To paraphrase the title of a deservedly well-known play and motion picture, we will need men who are not only interpreters for all seasons, but interpreters for all wavelengths.) Some will be area specialists, others will cut at right angles and be functional specialists. (For example: we might have a man specializing in West Boondakistan, and another man specializing in railroads. Their interests intersect but clearly are different.) There will be specialized viewers and projection apparatus, measuring instruments of various sorts, automatic isodensitometers, and recording microdensitometers. We will need darkrooms, photo labs, and mass printing and transparency production facilities, for both black-and-white and color film end products.

We will need library and filing facilities, with retrieval of various types of data. Computers and their human assistants will be needed in quantity.

This description only scratches the surface. Besides what's in the building, we will require communication equipment and people -- to direct, question, and intersect with ground truth teams checking specific items in field locations. Printing and publishing facilities will likely be required -- for putting in useful form the varied outputs of the analysis center.

How big an operation are we talking about? Organizations somewhat similar but not identical to the one herein postulated already exist -- reconnaissance technical squadrons (RTS), the Army Map Service, and the Aeronautical Chart and Information Center. Reflection and analysis makes not unreasonable the observation that for each photo-interpreter, there are about ten men behind him -- laboratory technicians, plotters, printers, librarians, computer personnel, typists, editors, etc. We haven't even mentioned administrative overhead, that component of all organizations which incurs obvious and visible costs without producing tangible benefits.

In our building, concerned as we will be with many subjects, wavelengths, and special topics (and above all, huge areas), it is unlikely that we can get by with only 25 interpreters; it is painful to contemplate, and hence unlikely, that we will need as many as 2500. Let's take the geometric mean, and call for 250. This is not unreasonable. Using the 10:1 backup figure produces an estimate of 2500 people. A conservative estimate for the cost of the building, fully equipped, would be about 15 to 20 million dollars. Annual operating cost for the 2500 people would be about 50 million dollars.

We don't -- and wouldn't dare -- propose to start full bore. A starter set for such an operation would be about 500 people, or 1/5 full scale. We are talking about using, on a production-line basis, uncommon and even nonexistent skills. There are few radar imagery interpreters who are used to working with nonmilitary objects or with subjects such as geology and crops. Despite almost twenty years of fooling with and flying infrared imagery-producing apparatus, there are pitifully few interpreters of this material and, again, still fewer who have paid attention to the nonmilitary fields. The ability to analyze, code, and decode the output from a multichannel recording spectrometer is still rarer than the other skills.

All this argues strongly for starting the analysis center on a small scale, learning, teaching, and developing skills, and <u>then</u> expanding. Better a little success than a huge flop!

It will be remembered that cost estimates for securing data over North and South America using aircraft and satellites were as follows:

To cover North and South America twice a year with an aircraft system	$\$15.5 \times 10^6$
To cover 80 percent of North and South America once with a three-camera photo satellite system	$\$100 \times 10^6$

The superficial first look at these two numbers developed a ratio of about 7:1 in costs. But the aircraft system did 36×10^6 mi^2 and the satellite system did only 80 percent of 17×10^6 mi^2. The ratio of \$/mi^2 is now about 18:1. Neither of the two sample (and simple) calculations above included analysis costs. If we assume annual costs of \$50 x 10^6 for analysis, and add this in, we get:

$$\frac{\text{Cost of 1 year satellite operation}}{\text{Cost of 1 year aircraft operation}} = \frac{100 + 50}{15.5 + 50}$$

$$= \frac{150}{65} = 2.3 \text{ to } 1$$

To sum up, analysis (i.e., getting and presenting usable, timely answers) is usually disregarded, left to chance, or underestimated. We don't need one more sad example to cast on the stockpile of history. If mistakes are to be made, let them be new ones. Making a new mistake is regrettable, but making an old one over again is stupid.

V. HOW TO START

The application of a new technique -- such as measuring, exploring, or mapping earth resources from data secured by spaceborne sensors -- usually requires that the realizable benefits exceed the cost of securing those benefits. The "usually" in the preceding statement is not deployed frivolously, because some tasks need doing for the sake of extrinsic considerations in which the accomplishment of the particular task at hand is necessary to spark or catalyze other developments and thus to act as a multiplier.

Further, given a series of countries in varying states of development, one might develop a weighting system (confessedly simple-minded) that would reflect both the absolute value of the operation (for instance, using the GNP of the country), and the ease with which improvements in the country's economy can be made through the use of the proposed system.

The first of these two factors merely argues the obvious: that, all other things being equal (which they seldom are), a fixed percentage of a big amount is larger than the same percentage of a small amount. The second factor is simply the marginal utility. If a country is well-mapped, well-explored, well-inventoried, well-reported, etc., it is unlikely that an additional tool, such as that afforded by space sensing gear, will make as much difference as it would in another country, less-developed, less- etc. -- if in the second country there are ways and people ready to use the information on a taut leash, ready to go. Despite the protestations of the various specialists, the United States, to take a country at hand, is well-developed, well-mapped, etc. Certainly this is true by comparison with what are called "less-developed countries." It might be argued that the marginal utility of spacecraft sensors is lower for the United States than for a less-developed country.

Even if this conservative assumption is so (and taking India as an example of a less-developed country, one is hard-pressed to believe that in the foreseeable future India could better exploit resource surveys than could the United States), the economic multiplier of the United States is so huge that one will almost always come up with weighting factors that give the United States highest priority.

This result is not uncongenial. For a long time the equivocality of space-derived data and their interpretation will require that much ground truth be obtained to check and to supplement them. Much experimentation will be needed before international commitments of any variety are made. (This suggests that we hold our tongues internationally and do not force a country into the role of Tantalus by holding out benefits that we can't deliver.) We will have to shake the system down, debug it, and probably engage in uneconomic operations -- for a while. The United States can better afford operations in which cost exceeds benefit than can anyone else.

All this argues for doing in the United States what we think we're going to want to do on a global basis. It is much better to have private and internal difficulties than public and international difficulties.

VI. THE LIMITING CASE

The biggest problem area outside the United States (subject to the constraint that the United States have an active interest in helping the country and the country be "willing" to be helped) is India. O.K., let's take India.

Let's imagine the most favorable outcome of the earth resources satellite program: we've run the program, and it has worked. All desirable and needed data have been secured, reduced, analyzed, and put in usable form. Maps, land-use patterns, hydrologic, geologic, demographic data -- are all available, as are any data that one can conceive of wanting or using. Let's further suppose that we have an Indian Data, Information and Analysis Center (IDIAC), that the data are kept up to date, and that they are readily accessible and available in map, graphical, digital, or any other form.

O.K., now what? What can we (or India) do that will be significantly different than could be done with present data? How could such a cornucopia of new data be used? Will it make a difference? Are these data genuinely important, or will their importance and impact be vitiated by national habits, customs, mores, institutional problems, religious factors, and ineptitudes of various sorts?

These questions are raised not to prevent programs from getting off the ground, but to make sure that expectations are not raised unduly, and that the narrow perspective forced by technological blinders doesn't obstruct the full field of the problem. These questions are, of course, part of a broader series of questions. Can we expect India to take advice? Can we design and erect cooperative bilateral training centers? What does our cumulative experience with India to date suggest? Or, more directly, do we even understand the process of foreign aid to less-developed countries, when our understanding is based on happy -- but mainly irrelevant -- models drawn from our experiences with western, sophisticated, Marshall Plan countries?

Going to the limits, as in this example, can help clarify assumptions, moderate expectations, and illuminate otherwise dark corners, and thus help to chart a smooth passage. This is not a plea for scientists to stop working on scientific problems and start working on socio-political problems -- any more than it is the reverse. But if there is to be mutual benefit, the efforts on these two axes had better not be at right angles -- or there will be no cross-product. Scientists, engineers, and technologists working in or on space are immersed in and concerned with a physical vacuum. They must avoid working in a political vacuum as well.